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NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

EVIDENCE OF SUBARCTIC
WATER MASS INTRUSIONS
AT OCEAN WEATHER STATION NOVEMBER

by

John Francis Pfeiffer

September 1976

Thesis Advisor: R. H. Bourke

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A divergent heat budget equation which included the effects of surface heat flux, horizontal and vertical advection, and horizontal divergence on the near-surface heat content was used to examine the role of thermal advection in the upper 250m of the water column at Ocean Weather Station NOVEMBER. This station is located on the southern boundary of the transition zone separating the Subarctic water mass from the Subtropic

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water mass. Values for horizontal thermal advection changes were computed over the period 1962-1970. This term was correlated with salinity fluctuations over the period 1968-1970. Pulse-like periods of cool advection were associated with periods of reduced salinities suggesting these were intrusions of Subarctic water. Over the nine-year period of analysis, these intrusions had a periodicity of 7 to 8 months with a duration of 3 to 4.5 months. It is suggested these wave-like intrusions along the Subtropic front are the result of the passage of non-dispersive baroclinic Rossby waves.

Evidence of Subarctic Water Mass Intrusions
at Ocean Weather Station NOVEMBER

by

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ABSTRACT

A divergent heat budget equation which included the effects of surface heat flux, horizontal and vertical advection, and horizontal divergence on the near-surface heat content was used to examine the role of thermal advection in the upper 250m of the water column at Ocean Weather Station NOVEMBER. This station is located on the southern boundary of the transition zone separating the Subarctic water mass from the Subtropic water mass. Values for horizontal thermal advection changes were computed over the period 1968-1970. Pulse-like periods of cool advection were associated with periods of reduced salinities suggesting these were intrusions of Subarctic water. Over the nine-year period of analysis, these intrusions had a periodicity of 7 to 8 months with a duration of 3 to 4.5 months. It is suggested these wave-like intrusions along the Subtropic front are the result of the passage of non-dispersive baroclinic Rossby waves.

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I. INTRODUCTION

A. GENERAL

The heat content of the upper layers of the ocean has recently been of interest, particularly with respect to the factors or forces which alter the heat state. Changes in the heat content result in changes in the temperature structure and, with that, changes in the density distribution and oceanic layering. A knowledge of these factors and an attempt to predict and quantify their contributions is of importance to the United States Navy, especially with regard to anti-submarine warfare and its strong dependence on sound speed profiles which readily respond to alterations of the thermohaline structure.

B. THE HEAT BALANCE

An influential process in the alteration of the thermal structure begins at the air-sea interface with insolation, the rate at which short-wave energy from the sun enters the sea. This factor, combined with the effects of back radiation, evaporation, condensation, and conduction, produces a net surface heat exchange across the air-sea interface. In shallow water the effect of this net heat exchange is disproportionately large; in deep water its role as a significant process can vary with respect to other forces.

Redistribution of heat can occur via convective and mechanical mixing, the former primarily a seasonal process responding to the air-sea temperature differences, the latter responding to the effect of wind and waves. Both are significant in the layer above the main thermocline.

Advection, vertical or horizontal, is a process of transport of an oceanic property (e.g., temperature) solely by the mass motion of the ocean. Its importance as a major heat contributor has been uncertain. Studies as recently as Thorne [1974] have computed horizontal thermal advection as the difference between the surface heat exchange (Q_n) and the local change in heat content ($\partial H/\partial t$). However, no correlations between the changes in horizontal advection and those of net surface heat flux, atmospheric pressure, or salinity were undertaken to support the validity of the model. It appears from this work and others [Tabata, 1961; Clark, 1967; Bathen, 1970] that horizontal advection does not completely account for the difference between local change in heat and net surface exchange; additional processes must be considered to account for this difference.

Emery [1976] assumed that, in addition to Q_n and horizontal advection ($-\vec{V}_h \cdot \nabla_h H$), vertical advection and the compensatory action of horizontal divergence/convergence were major heat processes in the upper layer of the ocean. Correlation studies which included these additional terms suggested that they played a significant role in the heat budget of the upper ocean. Emery developed a divergent heat budget (DHB) equation to model the correlation of these terms with the heat content of the upper layers. However, the contribution of each of the DHB terms to the heat balance was not specified nor were they correlated with changes in physical properties, e.g., salinity or oxygen.

C. OBJECTIVES

The purpose of this study was to complete and extend the findings of these earlier investigations. Specifically, the objectives of this research were:

- to quantify each expression in the DHB equation
- to determine the following trends
    - mean annual
    - yearly by month
    - anomalies
- and in particular, to examine the significance of horizontal advection in changing the heat content of the upper ocean and to determine the validity of the results by correlation with other oceanic parameters.

D. METHODOLOGY

In order to measure horizontal thermal advection ($-\vec{V}_h \cdot \nabla_h H$), one must either possess a large horizontal data field of temperature and velocity to calculate the advective term directly, or deal with temperature and salinity measurements from a point source which necessitates accounting for all the expressions in the heat balance and attributing the residual to horizontal advection. In either case, it is important to validate the horizontal advective heat process by comparing changes in the thermal structure with changes in a physical property such as salinity. Such a thermohaline re-structuring can be the result of water mass intrusions.

Therefore, in order to realize the objectives of this research, a long-time data record is needed as well as a location that is readily influenced by water mass intrusions. Ocean Weather Station NOVEMBER (OWS N) affords such an opportunity, since it offers both a long period of data and is strategically positioned at the transition zone between the Subarctic and Subtropical water masses.

The Subarctic water mass is a cool, low-salinity body of water occupying the upper 300m of the Pacific Ocean, generally north of 40°N. Subtropical water is characterized by a shallow, warm, salty layer in the vicinity of 32°N. The transition zone between these water masses is characterized by sharp horizontal heat and salinity gradients [Roden, 1976].

II. THEORY

A. GENERAL

In his examination of the role of vertical motion in the heat budget of the upper 250m of the ocean, Emery [1976] found changes in the heat content ($\partial H/\partial t$) at OWS N could only be moderately explained by changes in heat across the air-sea interface (Q_n). However, heat content changes could be explained far more accurately when two additional processes, horizontal divergence and vertical advection, were incorporated with the surface heat flux. To establish this correlation, he developed a divergent heat budget (DHB) equation which included these processes.

The major assumptions in the development of the DHB equation are:

- Molecular diffusion and radiative heat flux out of the column are neglected.
- The field of motion is comprised of a steady mean flow upon which are superimposed internal Rossby waves with periods from months to years.
- Temperature changes at the bottom of the water column can be attributed mainly to vertical advection of the mean thermal gradient at that depth. Since the base of the column is always beneath the main thermocline at OWS N, turbulent energy at this depth is small; therefore, temperature changes due to turbulent mixing can be considered negligible.

Starting with the equation for the conservation of heat and by incorporating the above assumptions along with a Reynolds decomposition to the temperature and velocity expressions, Emery arrived at the divergent heat budget equation,

$$\partial H/\partial t - \frac{W_D}{D}\,[H - \rho C_p D T_D] + \vec{V}_h \cdot \nabla_h H = Q_n \qquad (1)$$

$$1 \qquad\qquad 2 \qquad\qquad 3 \qquad 4$$

where term 1 is the local change in heat content of a column of water of depth D; term 2 is the heat change due to horizontal divergence ($W_D H/D$) and vertical advection ($\rho C_p W_D T_D$) through the bottom of the column; term 3, the change due to horizontal advection; and term 4, the resultant gain or loss of heat across the air-sea interface. Term 2 may be combined as shown and expressed as H_{div}, the net change in heat content due to near-surface divergence/convergence and the compensatory upwelling/downwelling mechanism.

Q_n is comprised of the following major terms,

$$Q_n = Q_s - Q_b - Q_e - Q_h \qquad (2)$$

where

Q_s = the rate at which short-wave energy from the sun enters the sea.

Q_b = the net long-wave back radiation from the sea surface.

Q_e = the net latent heat transfer (includes evaporation and condensation).

Q_h = the net sensible heat transfer (conduction).

H represents the heat content per unit surface area, evaluated for the upper 250m, and is computed by

$$H = \int_0^{250} \rho C_p T \, dz \tag{3}$$

where ρ is the density and C_p is the specific heat at constant pressure.

W_D, the mean vertical velocity, is computed by

$$W_D = \frac{-\partial T_{D}/\partial t}{\partial T_{D}/\partial z} \tag{4}$$

which assumes that temperature changes at D are due mainly to vertical advection of the mean thermal gradient at D. $\partial T_{D}/\partial t$ represents the monthly temperature change at 250m and $\partial T_{D}/\partial z$ is the mean vertical temperature gradient at 250m.

B. SIGN CONVENTION

The following sign convention is explained to aid in later physical interpretation of the results (refer Figure 1). Taking z positive downward and rearranging equation (1) to solve for the change in heat content in the water column,

$$\partial H/\partial t = \underset{1}{Q_n} + \underset{2}{W_D/D\,[H - \rho C_p D T_D]} - \underset{3}{\vec{V}_h \cdot \nabla_h H}. \tag{5}$$

1. <u>Net Surface Heat Exchange, Q_n</u>

A positive value for Q_n indicates that the column of water gains heat as the net result of the various heat

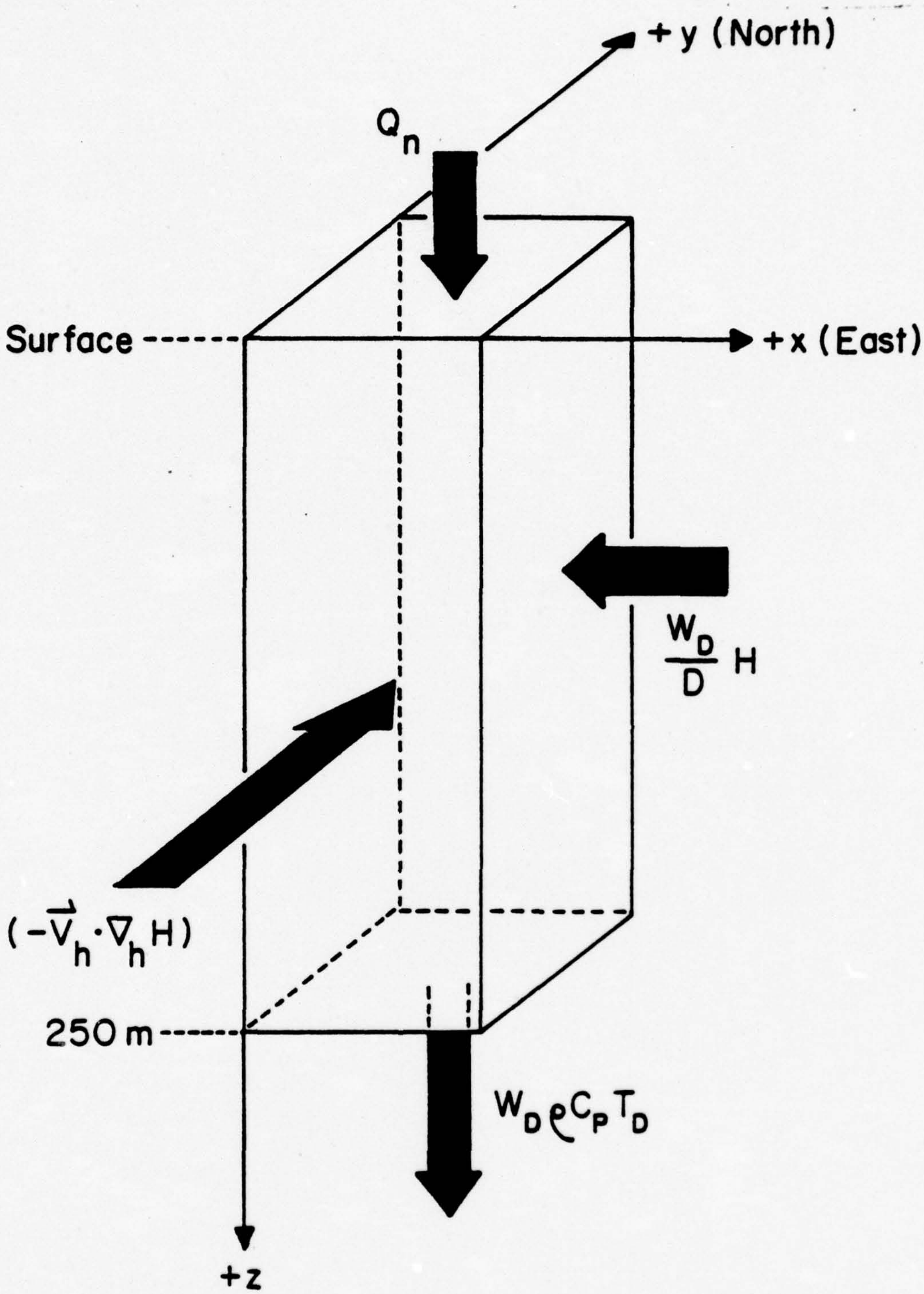

Figure 1: Direction of positive (heating) values for the DHB terms.

exchange processes acting at the air-ocean boundary [equation (2)]; negative values indicate that the ocean releases heat to the atmosphere via these processes.

2. Divergent Heat Change, $H_{div} = W_D/D\,[H - \rho C_p DT_D]$

a. $[H - \rho C_p DT_D]$ is always positive since it represents $\rho C_p(\bar{T} - T_{250})$ where $\bar{T}$ is the average temperature throughout the column.

b. From equation (4), W_D can be either positive or negative. Examination of the records shows that at OWS N $\partial T_D/\partial z$ is always negative at D = 250m. If $\partial T_D/\partial t$ were positive, i.e., a heating process, then a positive W_D results (downward vertical velocity). A negative W_D (upwelling) represents cooling. It follows then that term 2 of equation (5) responds directly to the sign of W_D. Therefore, the cooling process is characterized by an upward vertical velocity (W_D negative), accompanied by an outward flow across the vertical sides of the column (divergence) in accordance with the law of continuity. Downward vertical velocity and inward flow are associated with heating.

3. Horizontal Advection $(-\vec{V}_h \cdot \nabla_h H)$

Expanding the horizontal advection term into its component parts yields

$$-\vec{V}_h \cdot \nabla_h H = -(\bar{u}\hat{i} + \bar{v}\hat{j}) \cdot (\partial H/\partial x\ \hat{i} + \partial H/\partial y\ \hat{j}). \quad (6)$$

In the vicinity of OWS N isotherms are generally zonally distributed, hence horizontal advection reduces to $(-\bar{v}\partial H/\partial y)$. The north-south temperature gradient, $\partial T/\partial y$ is generally negative and can be appreciable when the southern boundary of the Subarctic/Subtropic transition zone migrates to the position of OWS N [Roden, 1976]. Positive horizontal advection indicates that heat is carried into the column generally under conditions of a northward flowing current. A cooling process is generally in response to a flow from the north. When horizontal advection is due to the passage of an eddy, the flow direction cannot be readily inferred. Whether heat is gained or lost is dependent on the sign of the horizontal temperature gradient, i.e., whether a warm core or a cold core eddy is involved in the advection.

III. ANALYSIS OF DATA

A. SOURCE OF DATA

Mechanical bathythermograph (MBT) data have been taken two to four times daily at OWS N since 1947. Monthly means of temperature at 5m intervals have been produced by Ballis [1973] from this data file. Significant gaps exist in these data for the earlier years, limiting a detailed analysis to the nine years, 1962-1970. In addition, MBT casts were limited to 135m prior to 1962, a depth too shallow for use in this study as the mixed layer is often slightly deeper than this depth, especially in winter.

Within the 1962-1970 MBT time series, minor data gaps were eliminated by incorporating temperature data from the daily hydrocasts taken at OWS N since 1964 and on file at the National Oceanographic Data Center (NODC). Although the monthly means calculated from the hydrocast data are based on fewer observations than those from the MBT data, no significant difference was detected between either data set. Standard deviations were similar and for those months when both sets of data existed, little difference in mean values was noted.

A salinity time series was created from the NODC hydrocast data. Data gaps limited this series to the period 1968-1970 since only a few short records existed prior to 1968.

Monthly means and anomalies of the net surface heat exchange (Q_n) were taken from the report by Rabe and Bourke [1975] which examined the various surface heat exchange processes at OWS N. These data are based on three-hourly observations from whence mean daily values for each month were calculated from standard bulk flux formulae. The dominant heat flux term, net solar insolation (Q_s), was calculated from the improved version of the Q_s equation developed by Seckel [1973].

B. ANALYSIS TECHNIQUE

Of the terms in the divergent heat exchange equation (1), the primary focus of this report was directed towards the horizontal advection term ($-\vec{V}_h \cdot \nabla_h H$). This is a residual term computed from the difference between the observed change in heat content ($\partial H/\partial t$) and the computed values of surface heat flux (Q_n) and divergent heat flux (H_{div}). This type of analysis affords the possibility of error accumulation in the residual term. However, it will later be shown that, in spite of the possibility of error accumulation, the large anomalies in horizontal advection are significantly greater than the potential error contribution.

1. Determination of Local Heat Change

Changes in the heat content of the water column are evaluated in this study on a seasonal scale by analyzing the temperature profiles from the MBT data of Ballis [1973] and the hydrocast data of Rabe and Bourke [1975]. These monthly observations can be considered, in most cases, to be centered about the 15th of the month, since most monthly observations were taken over the entire 30-day period. Some monthly means were skewed to either side of the 15th in response to the biased nature of the data collection, e.g., temperature data for May 1968 were collected between the 12th and the 31st, shifting the effective mean date for this month to 21 May. It then follows that the average monthly heat content of the upper 250m, $\overline{H}$, can be determined from these mean temperature profiles and assigned the same effective date. The mean heat content of the column is found from

$$\overline{H} = \int_0^{250} \overline{\rho C_p} \overline{T} \, dz \qquad (7)$$

where $\overline{\rho C_p}$ is the product of the mean water density and specific heat, assumed constant at 0.978 g-cal cm^{-3} °C^{-1}, and $\overline{T}$ is the mean temperature profile over the specified time interval.

The average monthly heat content was computed for the period 1962-1970; $\partial\overline{H}/\partial t$ was subsequently determined for the interval between successive $\overline{H}$'s. The interval, ∂t, ranged from 23 to 52 days. Values are computed in langleys per day (ly day^{-1}).

2. Net Surface Heat Exchange

The monthly mean daily values of $\overline{Q}_s$, $\overline{Q}_e$, $\overline{Q}_b$, and $\overline{Q}_h$ were combined to determine the monthly mean daily contribution of net surface heat exchange, $\overline{Q}_n$.

3. Heat Divergence ($\overline{H}_{div}$)

As previously discussed, $\overline{H}_{div}$ is the expression that includes heat exchange due to horizontal divergence and vertical advection, where $\overline{W}_D = -\partial\overline{T}_{D/\partial t}\,[\,\partial\overline{T}_{D/\partial z}]^{-1}$. Similar to the procedure used to calculate $\partial\overline{H}/\partial t$, $\partial\overline{T}_D/\partial t$ was computed from the mean temperature at 250m, i.e., $\overline{T}_D = \overline{T}_{250}$ over the specified time interval, the interval between effective dates. The temperature gradient ($\partial\overline{T}_D/\partial z$) at 250m was computed from the mean temperature profiles between 150 and 250m. This value ranged from -0.043 to -0.069 °C m^{-1}.

4. Example of Computation Process

The following is an example of the analysis technique applied to May and June 1968 (see Table I).

a. Effective Date

As shown in the listing of the daily distribution of MBT observations for each month [Ballis, 1973], MBT casts for May 1968 were made daily between the 12th and the 31st; no observations were taken prior to the 12th. Therefore, the effective data for the mean monthly temp, $\overline{T}_{May}$, is 21 May. Examination of the following month's record indicates at least one lowering per day was taken every day of the month (the most common situation). Hence the effective date, $\overline{T}_{June}$, is 15 June. The time interval (∂t) between $\overline{T}_{May}$ and $\overline{T}_{June}$ is established as 25 days.

Table I. Extract from mean monthly temperature profiles prepared by Ballis, 1973.

MAY T(C)	MAY SDV (σ)	MAY DAYS	JUNE T(C)	JUNE SDV (σ)	JUNE DAYS	DEPTH
20.00	.87	20	22.65	.59	29	0
19.97	.84	20	22.64	.60	29	5
19.87	.73	20	22.61	.60	29	10
19.66	.57	20	22.56	.62	29	15
19.46	.43	20	22.48	.68	29	20
19.27	.34	20	22.31	.82	29	25
19.07	.29	20	21.94	.93	29	30
18.86	.26	20	21.41	.94	29	35
18.75	.25	20	20.84	.77	29	40
18.65	.25	20	20.40	.57	29	45
18.54	.26	20	20.14	.51	29	50
18.47	.28	20	19.94	.47	29	55
18.42	.29	20	19.77	.47	29	60
18.39	.30	20	19.61	.46	29	65
18.35	.30	20	19.47	.45	29	70
18.32	.29	20	19.32	.44	29	75
18.28	.29	20	19.17	.43	29	80
18.25	.29	20	19.04	.43	29	85
18.22	.29	20	18.90	.42	29	90
18.18	.30	20	18.75	.44	29	95
18.13	.30	20	18.61	.47	29	100
18.06	.30	20	18.44	.51	29	105
17.97	.31	20	18.29	.55	29	110
17.85	.33	20	18.13	.56	29	115
17.70	.37	20	17.93	.60	29	120
17.50	.38	20	17.71	.64	29	125
17.31	.42	20	17.45	.65	29	130

MAY T(C)	MAY SDV (σ)	MAY DAYS	JUNE T(C)	JUNE SDV (σ)	JUNE DAYS	DEPTH
17.05	.45	20	17.17	.66	29	135
16.75	.47	20	16.41	.62	12	140
16.42	.44	20	16.14	.59	12	145
16.10	.44	20	15.90	.53	12	150
15.80	.45	20	15.64	.51	12	115
15.48	.42	20	15.36	.45	12	160
15.21	.40	20	15.09	.40	12	165
14.92	.39	20	14.83	.37	12	170
14.65	.36	20	14.60	.34	12	175
14.38	.34	20	14.36	.37	12	180
14.13	.33	20	14.12	.36	12	185
13.88	.33	20	13.90	.37	12	190
13.67	.32	20	13.65	.37	12	195
13.44	.32	20	13.42	.38	12	200
13.21	.31	20	13.16	.36	12	205
12.96	.32	20	12.93	.33	12	210
12.74	.32	20	12.68	.32	12	215
12.53	.31	20	12.50	.32	12	220
12.33	.28	20	12.31	.33	12	225
12.15	.28	20	12.08	.32	12	230
11.99	.29	20	11.87	.30	12	235
11.81	.27	20	11.68	.28	12	240
11.65	.28	20	11.51	.29	12	245
11.49	.27	20	11.35	.28	12	250
11.35	.26	20	11.18	.31	12	255
11.27	.30	20	11.07	.33	12	260
11.10	.25	20	10.94	.30	12	265
11.00	.25	19	10.83	.30	12	270

b. Heat Content

The mean monthly heat content was computed by integrating the mean monthly MBT profile [Ballis, 1973] to 250m at 5m intervals. From equation (7),

$$\overline{H}_{May} = 401{,}000 \text{ gm-cal cm}^{-2} \text{ (langleys = ly)}$$

$$\overline{H}_{June} = 418{,}600 \quad \text{ly}$$

It follows that the $\partial\overline{H}/\partial t$ for this 25-day period is a heat gain of 17,600 ly or an average daily heat gain of 700 ly day^{-1}.

c. Vertical Velocity

Recall that

$$\overline{W}_D = - \frac{\partial\overline{T}_{250}/\partial t}{\partial\overline{T}_{250}/\partial z} \quad ;$$

(1) <u>For May</u>

$$\frac{\partial\overline{T}_{250}}{\partial_3} = \frac{[11.49 - 16.10]°C}{250 - 150m} = -0.0461°C \ m^{-1} \ ;$$

(2) <u>For June</u>

$$\frac{\partial\overline{T}_{250}}{\partial_3} = \frac{[11.35 - 15.90]°C}{250 - 150m} = -0.0455°C \ m^{-1} \ .$$

Therefore, the effective vertical temperature gradient during the 25-day interval separating the average profiles is $-0.0458°C \ m^{-1}$.

(3) Change in Temperature at 250m

$$\frac{\partial \overline{T}_{250}}{\partial t} = \frac{[11.35 - 11.49]°C}{25 \text{ days}} = -0.0056°C \text{ day}^{-1} .$$

Therefore,

$$\overline{W}_D = -\frac{[-0.0056]}{[-0.0458]} = -0.122 \text{ m day}^{-1} .$$

d. Average Net Surface Heat Exchange, $\overline{Q}_n$

Average daily $\overline{Q}_n$

May : 224 ly day^{-1}

June: 227 ly day^{-1}

The average net surface heat exchange for the period 21 May-15 June is:

$$\overline{Q}_n \cdot \frac{[224][10 \text{ days}] + 227 \; [15 \text{ days}]}{25 \text{ days}} = 225.8 \text{ ly day}^{-1}$$

e. $\overline{H}_{div}$

The $\overline{H}_{div}$ term is dependent upon the mean heat content in the column between the effective dates $(\overline{\overline{H}})$ and the mean temperature at 250m over this same period $(\overline{\overline{T}}_{250})$:

$$\overline{H}_{div} = \frac{\overline{W}_{250}}{250m} \left[\overline{\overline{H}} - C_p D \rho \overline{\overline{T}}_{250} \right]_{D = 250m} ;$$

From 4.b. and Table I,

$$\overline{\overline{H}} = \frac{418{,}600 + 401{,}000}{2} = 409{,}850 \text{ ly} ;$$

$$\overline{\overline{T}}_{250} = \frac{11.49 + 11.35}{2} = 11.42°C .$$

f. Horizontal Advection ($\overline{-\vec{V}_h \cdot \nabla_h H}$)

Solve the remaining terms in equation (1) where D = 250m :

$$\overline{-\vec{V}_h \cdot \nabla_h H} = \frac{\partial \overline{H}}{\partial t} - \overline{Q}_n = \frac{\overline{W}_D}{D} [\overline{\overline{H}} - \rho C_p D \overline{\overline{T}}_D]$$

$$= [\frac{17600}{25}] - 225.8 - [\frac{-0.122}{250}]$$

$$[409{,}850 - (0.978)(2.5 \times 10^4 \text{ cm})(11.42°C)]$$

$$= 538 \text{ ly day}^{-1} \quad \text{(a heating process)} .$$

This is the average daily contribution to the heat column over the period from 21 May to 15 June 1968.

IV. RESULTS

A. GENERAL

Emery [1976] showed that the mean annual cycles of heat content within the mixed layer and within the upper 250m of the water column were significantly out-of-phase. This indicates that below the main thermocline, where turbulent kinetic energy is minimal, there are additional factors involved in the heat transfer process other than horizontal advection. Noting the fluctuations of the 14°C isotherm at both the short and long time scales, Emery assumed that vertical motion at 250m contributed significantly to the variability in the heat content and should be included in any conservation of heat equation.

As illustrated in the preceding section, the magnitude of these vertical terms and the net surface heat exchange were computed from the monthly mean temperature profiles. The remaining contribution to the observed change in the heat content was attributed to horizontal advection, a term not computed specifically, but determined as a residual from the DHB equation. The mean local change in heat content $\overline{(\partial H/\partial t)}$ is plotted for the period 1962-1970 (Figure 2). A plot of the factors which contribute to the local heat change ($\overline{Q}_n$, $\overline{H}_{div}$, $-\overline{\vec{V}_h \cdot \nabla_h H}$) are plotted for the same period in Figure 3.

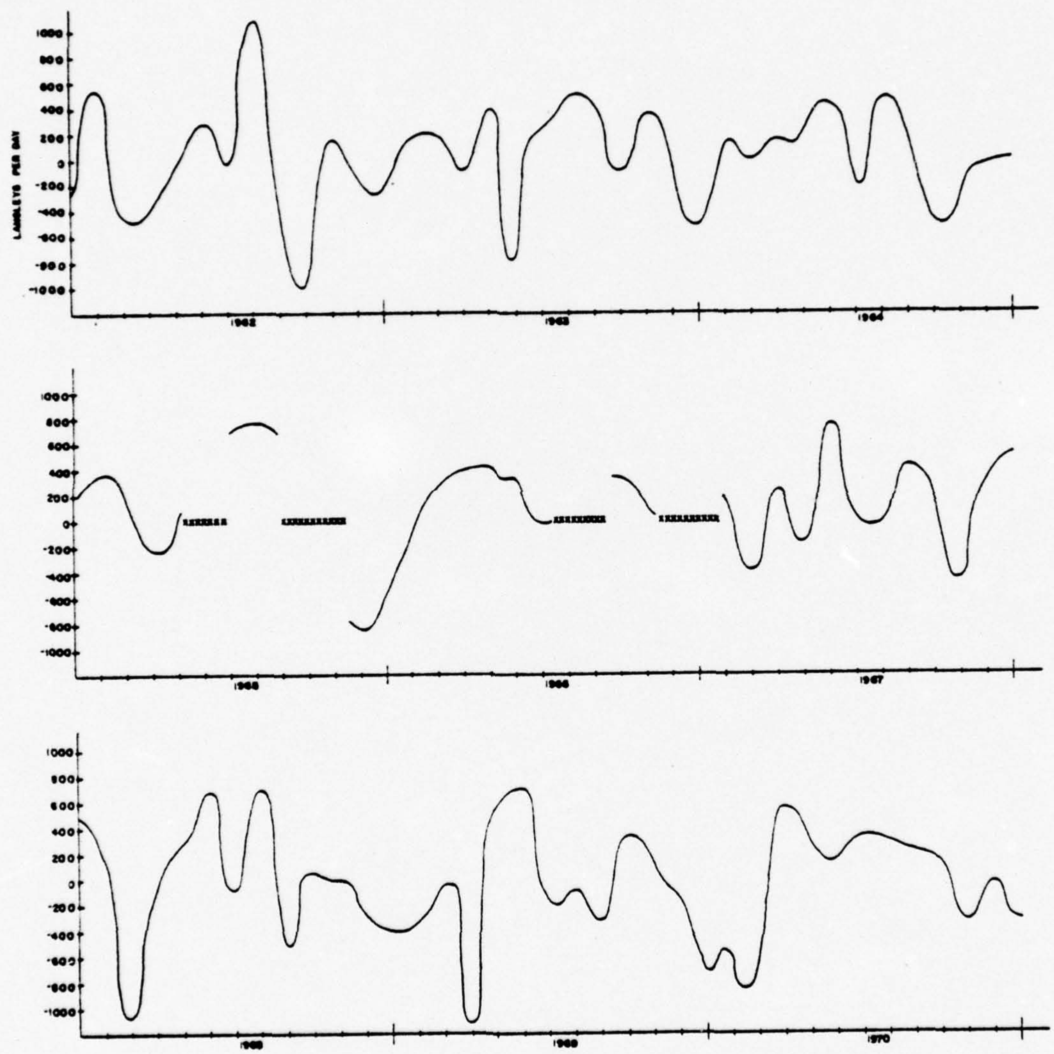

Figure 2: Nine-Year plot of the monthly change in heat content ($\partial H/\partial t$) in the upper 250m at OWS N.

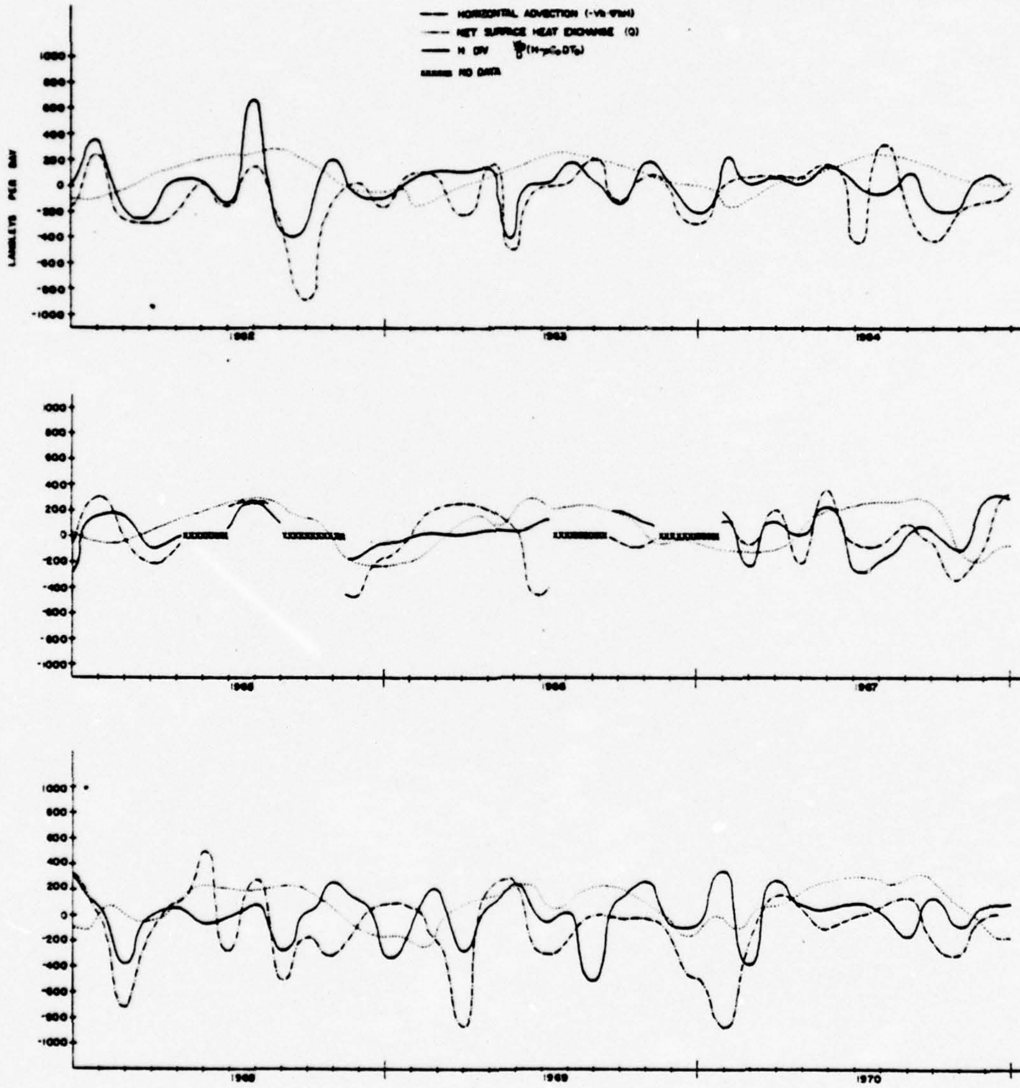

Figure 3: Nine-year plot of the major contributors to the monthly heat change (∂H/∂t) at OWS N.

One immediately notices in Figure 2 the pulse-like occurrences of large anomalies in the local heat change, especially the numerous events of large heat withdrawal, e.g., February 1968 and April 1969. Comparing this time series with the corresponding values of the DHB terms of Figure 3, one notices that the pulse-like nature of the large anomalies in $\partial H/\partial t$, which is physically measured, cannot be satisfactorily accounted for by Q_n or H_{div}, since the former exhibits no pulse-like anomalies and those of the latter are small. It is horizontal advection, in fact, which must account for the large fluctuations in the $\partial H/\partial t$ time series. Emery showed that upwelling, which is reflected in the H_{div} term, operates to change the relationship between Q_n and $\partial H/\partial t$. However, this does not mean that H_{div} automatically acts as the major influence in the balance of heat. What Emery has done, in fact, in his examination of the role of vertical motion in the heat budget, is to make more reliable the approximation of the horizontal advection contribution. Therefore, of the DHB terms, the primary interest of this study lies in the role that horizontal thermal advection plays in altering the heat content of the upper layers of the water column from year to year. Since $-\vec{V}_h \cdot \nabla_h H$ is a residually-determined expression which is potentially contaminated by measurement and modeling inaccuracies, it is necessary to evaluate whether the magnitude and fluctuations of the term bear any resemblance to physical reality.

One possible approach is through water mass analysis, since the transport of heat is usually accompanied by the transport of other properties such as salinity or dissolved oxygen. Water mass analysis through temperature and salinity correlations is particularly useful at OWS N since it lies on the southern edge of the transition zone between the Sub-arctic and the Subtropical water masses, a frontal boundary distinguished by its sharp horizontal and vertical gradients. The position of OWS N is fortuitous since any significant intrusion of cool, low-saline, Subarctic water should strongly influence the thermohaline structure of the upper 250m.

Correlation of salinity changes with thermal advection changes at OWS N is necessarily limited to the three years, 1968 through 1970, due to a lack of salinity data for the previous years. However, because of the good correlation between salinity and thermal advection during 1968-1970 (shown later in this section), one can surmise that thermal "events" of horizontal advection in the earlier years can be related to water mass intrusions.

First, the data will be analyzed by examining the mean annual contribution from each of the terms in the DHB equation, followed by a discussion of the major horizontal advective anomalies.

B. MEAN ANNUAL CYCLE

The mean annual cycle for each term in the DHB equation was calculated by averaging the mean monthly values from

1962-1970 (Figures 4 to 7). One must interpret the results with caution as the mean annual curves are based on a maximum of nine years of monthly averages, far too few to draw conclusive results.

The mean annual cycle of $\partial\overline{H}/\partial t$ (Figure 4) exhibits a broad general tendency for heating from April to September, followed by a cooling trend for the remainder of the annual cycle. The actual curve is a series of oscillations fluctuating about this trend by 200 to 300 ly day^{-1}. However, of the component terms in the DHB equation, only $\overline{Q}_n$ displays an annual cycle and is therefore the term which creates the cyclic trend in $\partial\overline{H}/\partial t$. The other terms appear to fluctuate as pulses and serve to enhance or to suppress the trend in surface heat flux.

The pulse-like nature of the horizontal advection term appears non-seasonal and is noticeably larger in most cases than $\overline{H}_{div}$ in its contribution to $\partial\overline{H}/\partial t$. If, as anticipated, its oscillatory nature is due to a water mass intrusion, the thermohaline structure of the environment should be significantly altered. Hence, salinity changes during any large advective cycle should also exhibit a pulse-like nature. This hypothesis is supported by Hansen [1973] who observed that surface salinity changes at OWS N were pulse-like occurrences displaying neither a seasonal trend nor a correlation with any seasonal process, e.g., evaporation minus precipitation.

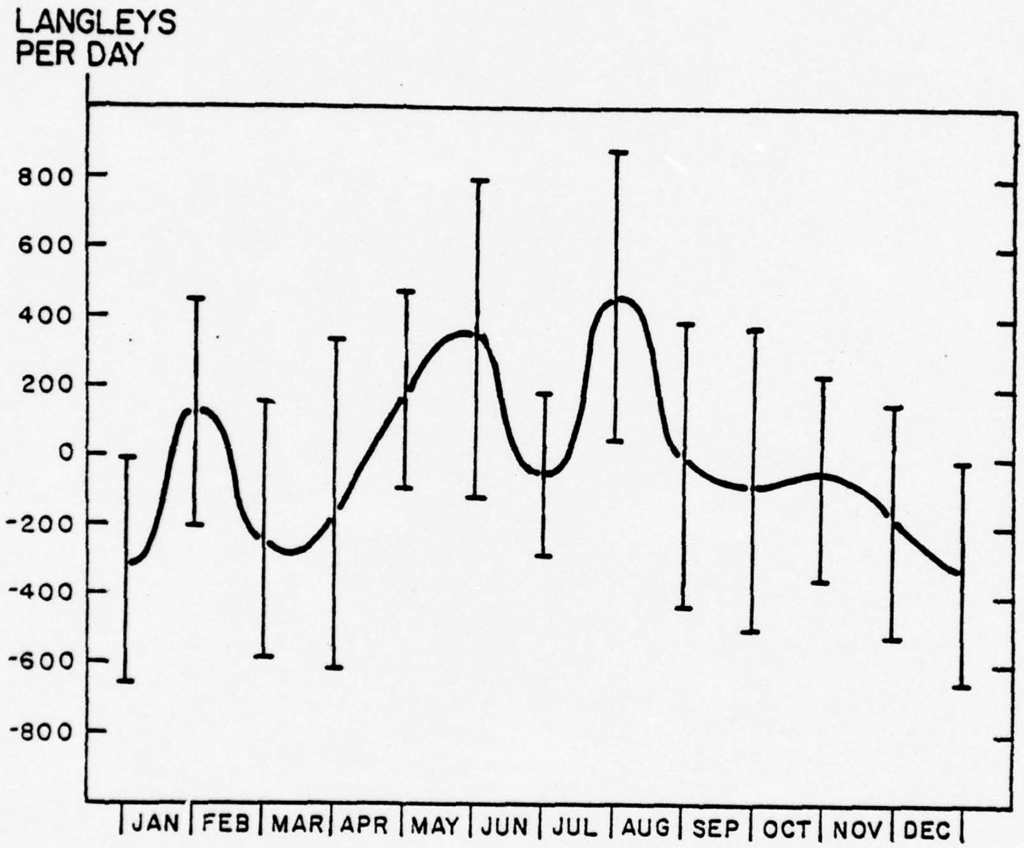

Figure 4: Mean annual trend in the monthly changes in heat content ($\partial H/\partial t$) at OWS N. Bars indicate one standard deviation ($\pm 1\sigma$)

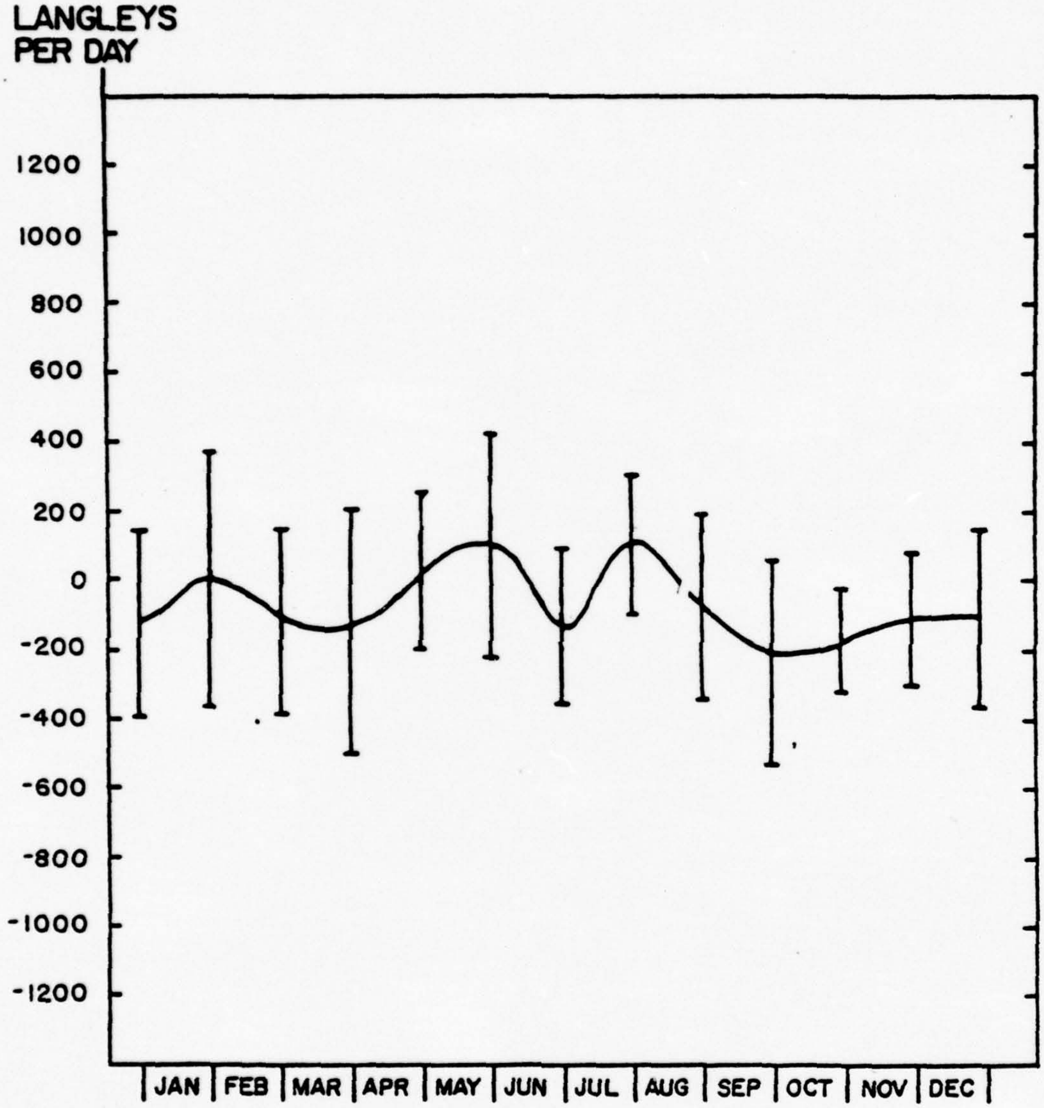

Figure 5: Mean annual trend in the horizontal advection contribution ($-\vec{V}_h \cdot \nabla_h H$) to local heat change ($\partial H/\partial t$) at OWS N. Bars indicate one standard deviation ($\pm 1\sigma$).

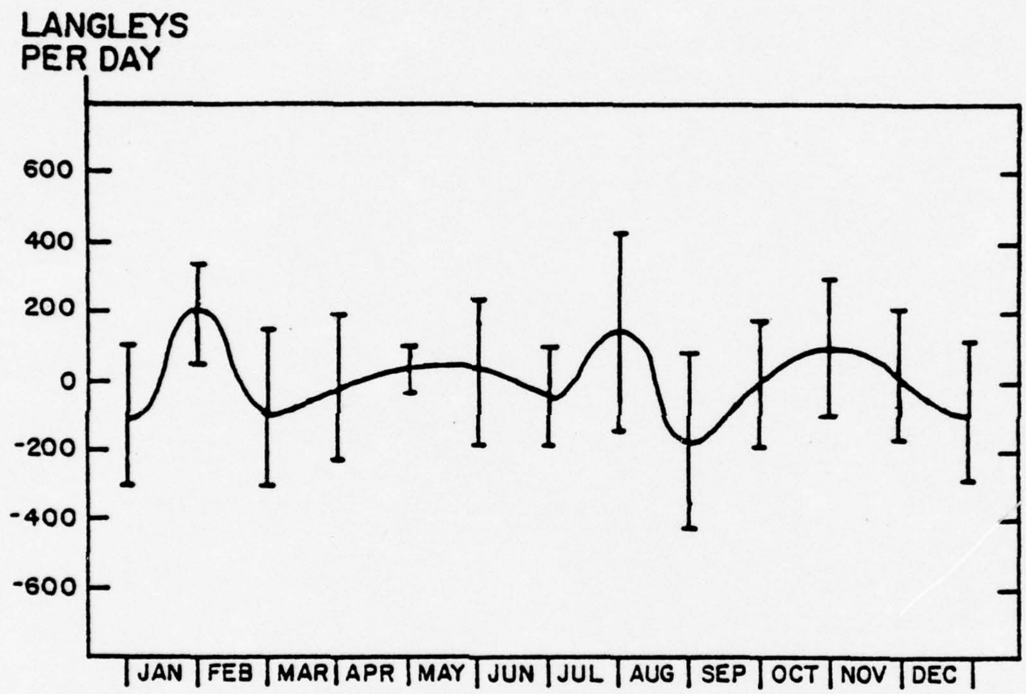

Figure 6: Mean annual trend in horizontal divergence plus vertical advection contribution (H_{div}) to the local heat change ($\partial H/\partial t$) at OWS N. Bars indicate one standard deviation ($\pm 1\sigma$).

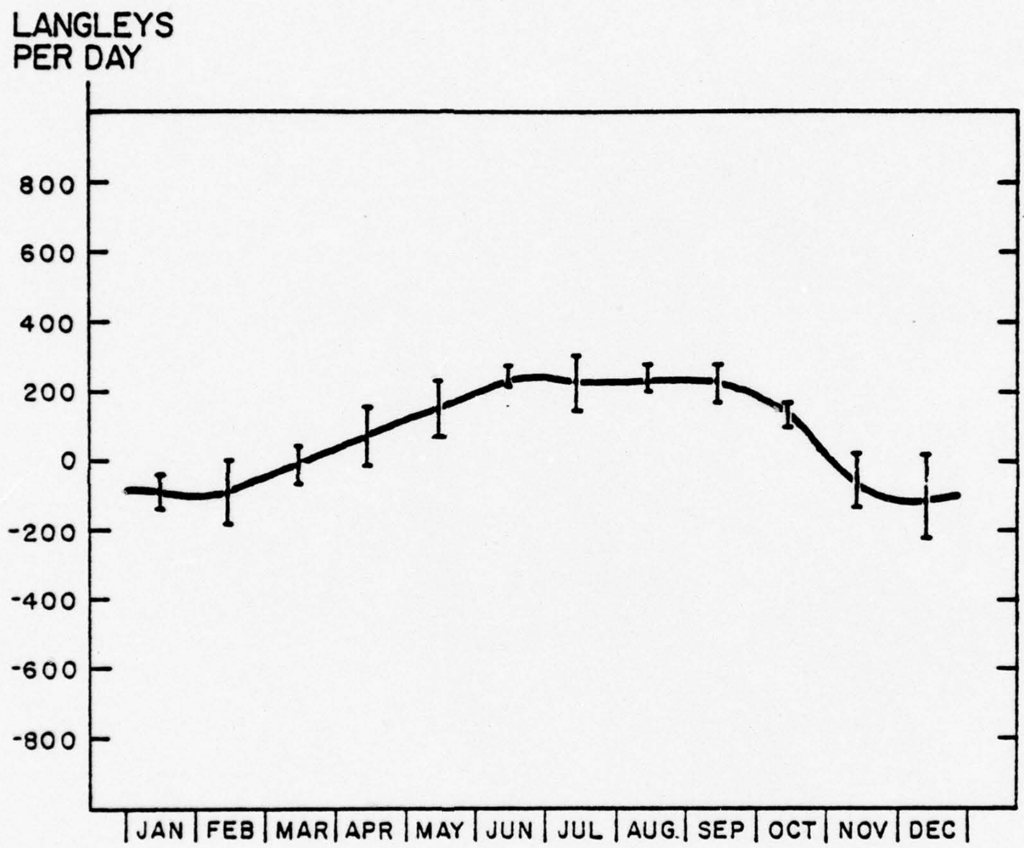

Figure 7: Mean annual trend of net surface heat exchange contribution (Q_n) to local heat change ($\partial H/\partial t$) at OWS N. Bars indicate one standard deviation ($\pm 1\sigma$).

C. HORIZONTAL ADVECTION ANOMALIES

The years 1968-1970 were highlighted by five distinct anomalies or events in horizontal advection. A detailed examination of each event is presented in Appendix A.

The initial phase of each of these irregularities was a sharp cooling trend followed by a substantial recovery period of warm advection. Rapid cooling of the water column occurred over a period of 25 to 30 days causing the heat reduction by horizontal advection to increase from near zero values to approximately 300 to 850 ly day^{-1} at the peak of the cold water intrusion. Thus, the daily change of heat loss during these cooling periods was approximately 10-23 ly day^{-1}.

A rebound to initial conditions occurred following these cooling peaks over approximately the same time period as the cooling trend. Typically, the return to mean conditions was followed by an overshoot of heating, peaking at 300 to 500 ly day^{-1}, eventually returning to mean conditions about 3 to 4.5 months after the intrusion of the low-temperature water mass.

Salinity changes during each of these events were significant at the surface and throughout the 250m water column (see Table II, Appendix A). Each thermal advection event was accompanied by a concurrent salinity change, i.e., the initial cooling trend was accompanied by a large salinity decrease throughout the column, while the rebound phase of warm advection was characterized by salinity increases.

The average changes at the surface, 50m, 150m, and 200m, during cooling trends were -0.21, -0.18, -0.17, -0.15°/₀₀, respectively. During the rebound phase mean salinity increases were 0.23, 0.16, 0.13, 0.10°/₀₀.

Since each horizontal advective cooling trend was characterized by a concurrent and significant decrease in the mean salinity and each advective heating trend was accompanied by an equally sharp salinity increase, it can be concluded that the major cause for these thermohaline fluctuations was the intrusion of the Subarctic and the Subtropic water masses.

Also note that in the nine-year time series (Figure 3) horizontal advection $(-\vec{V}_h \cdot \nabla_h H)$ and H_{div} do not necessarily fluctuate in phase. For example, refer to Events 1 to 5 in Figure 8. Note that in Events 1, 2, 3, & 5 the H_{div} term follows the trend of horizontal advection; in Event 4 H_{div} is oppositely directed.

An interesting phenomenon was noted in the salinity changes at 200m during these events. Events 1, 2, 3, & 5 are periods of cool horizontal thermal advection, i.e., intrusions of low-salinity Subarctic water. Simultaneously with these Subarctic intrusions, H_{div} indicates the occurrence of upwelling. During these trends, the salinity decrease at 200m averages -0.12°/₀₀. However, in Event 4, where the H_{div} term indicates that downwelling was occurring, the salinity change at 200m is a very large -0.34°/₀₀. A possible explanation for these salinity differences is that during each of these intrusions of Subarctic water, the temperature and

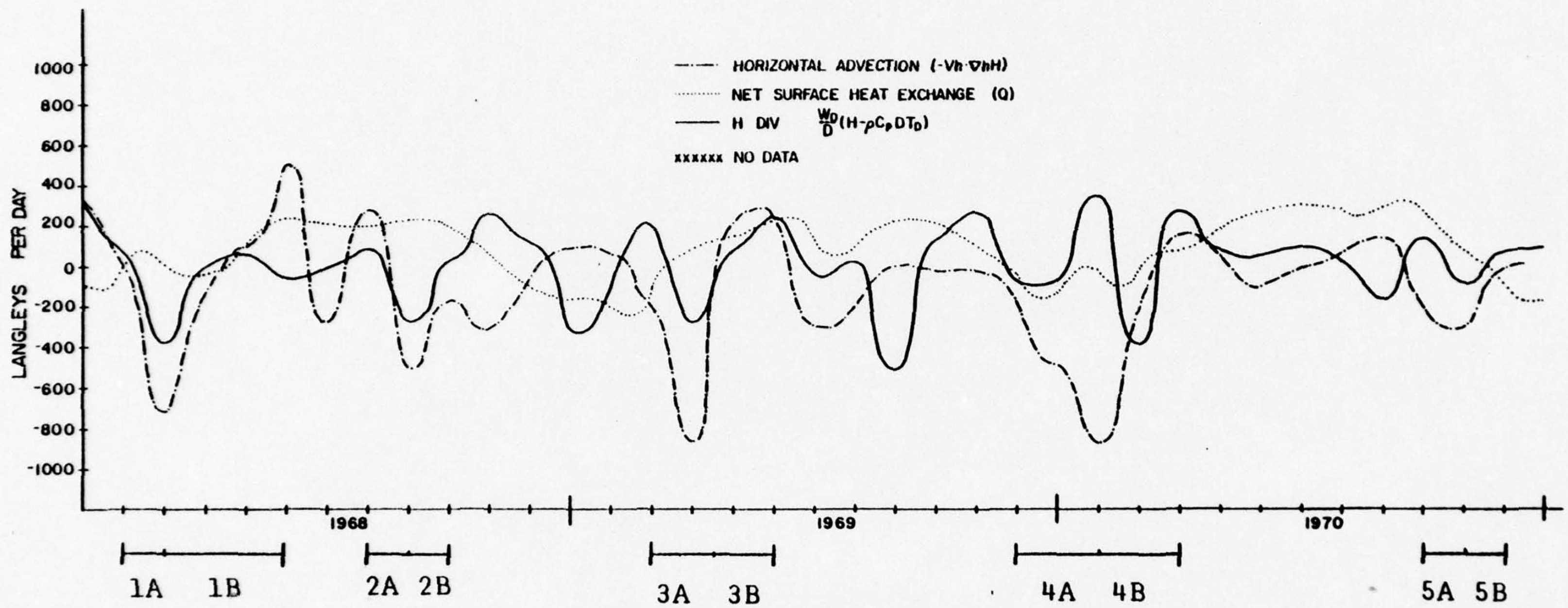

Figure 8: Major events in horizontal advection $(-\vec{V}_h \cdot \nabla_h H)$ for 1968-1970.

salinity in the upper layers are lowered. During coincident upwelling periods (H_{div} negative), the salinity decrease due to advection is suppressed by the introduction of higher salinity water from the lower portion of the Subarctic halocline (Figure 9). However, during Event 4 the downwelling action enhances the salinity reduction due to advection by mixing downward the lower salinity values of the upper halocline.

D. BAROCLINIC ROSSBY WAVES

These thermohaline changes suggest the intrusion and subsequent recession of the Subarctic water mass at OWS N in a pulse-like, non-seasonal manner. This translation of the boundary may be explained only partially by examination of surface wind stress since the resultant Ekman dynamics cannot fully account for the temperature and salinity fluctuations between the main thermocline and 250m.

The non-seasonal nature of the horizontal advection anomalies indicates that perhaps the driving mechanism itself is non-seasonal. An examination of atmospheric data from 1968-1970 reveals no unusual atmospheric pressure anomalies or significant weather deviations during the time of the large advective anomalies. What is apparent, however, about these pulse-like cooling/heating trends is their 7- to 8-month periodicity -- an indication perhaps that the southern boundary of the Subarctic/Subtropic transition zone might be responding to the passage of non-dispersive baroclinic Rossby waves, as suggested by Bernstein and White [1974].

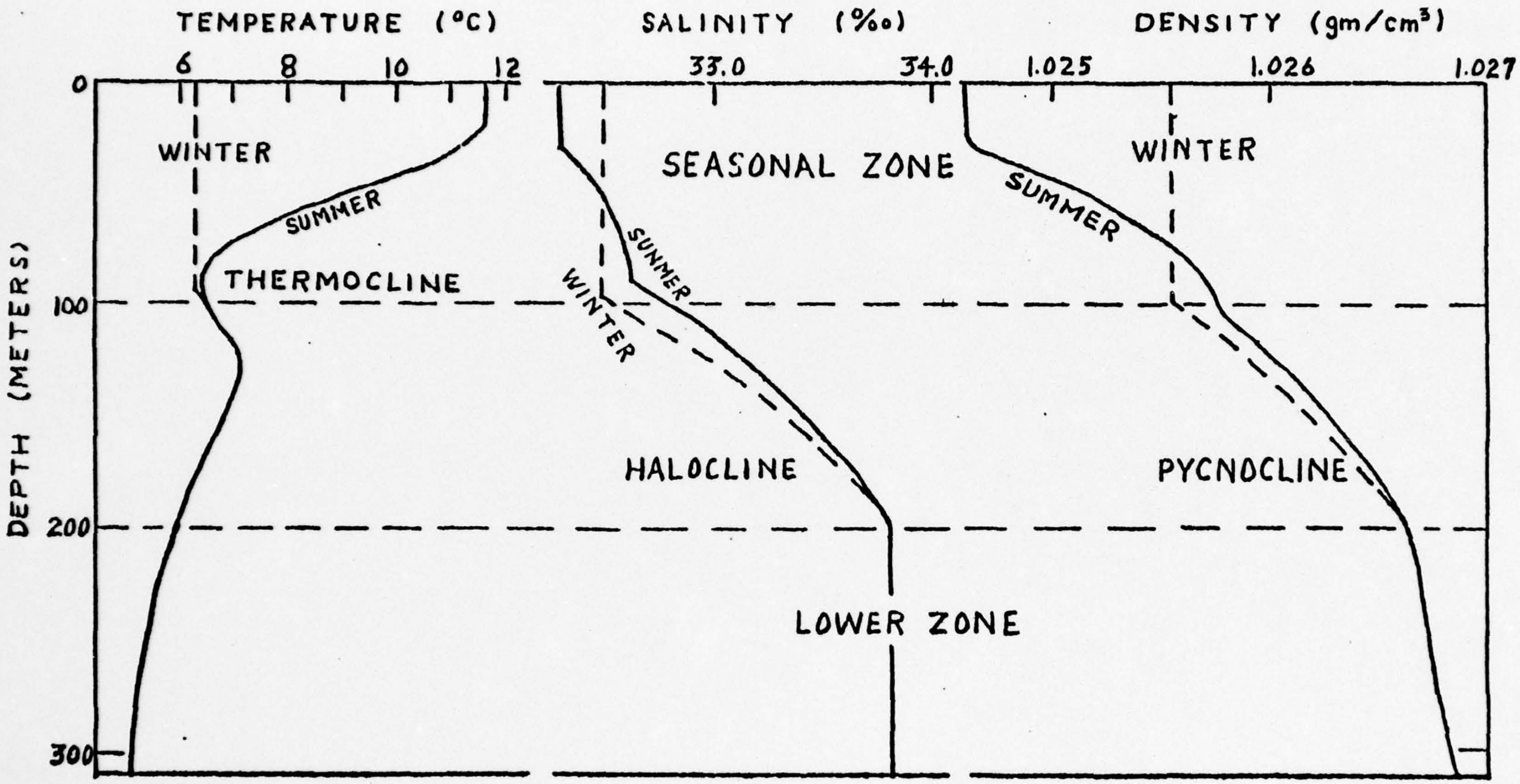

Figure 9: Typical temperature, salinity, and density structure in the Subarctic Pacific Ocean [after Tully, 1963].

In their study of the time and length scales of baroclinic eddies in the Central North Pacific Ocean, Bernstein and White examined the subsurface temperature fluctuations at OWS N using the MBT data compiled by Ballis [1973]. They determined that the large-amplitude fluctuations of the average monthly temperature at 200m, which was below any seasonal influence, could not be due to effects of internal waves or variations in the geostrophic flow. They noted a long-period fluctuation of six years upon which smaller variations occurred with periods of two to six months. They attributed these scales of motion to baroclinic, non-dispersive, Rossby waves. However, they were unable to localize the dominant period of maximum energy in the spectral density functions for the subsurface temperature profiles as their data record length (the same as used in this report) limited the maximum resolution to about six months. Much energy is undoubtedly contained in longer period waves. From his study of spectra from temperature records from the ocean weather ships in the Atlantic, Gill [1975] showed that the spectra are different at each station, but that large energy levels existed at periods greater than six months, especially for stations near frontal boundaries. It is suggested, then, that the 7- to 8-month occurrences of large advective cooling/heating, evident in this analysis, are the results of baroclinic Rossby waves.

E. SUMMARY

It is apparent that the effect of these wave-like eddies on the temperature and salinity structure near water mass boundaries can be substantial. Each of the large advective anomalies was characterized by an initial cooling trend, an indication that the southern edge of the transition zone at OWS N was being pushed southward. The thermal and salinity structure of the water column reacted accordingly to the intrusion of fresh, cool water from the north. As the eddy progressed westward, it allowed the transition zone boundary to "rebound" towards the north wherein the thermal and salinity structure responded to the return of the warm, saline subtropical water mass.

V. CONCLUSIONS

This study investigated the effects of horizontal thermal advection in the upper 250m at OWS N from 1962-1970.

In accordance with the divergent heat budget (DHB) equation, heat changes that were not due to the combined effects of net surface exchange, vertical advection, and horizontal divergence were attributed to horizontal thermal advection in maintaining the balance of heat in a column of water.

The investigation concentrated on the period 1968-1970 and centered on water mass analysis and its relation to the large anomalies in horizontal advection. The results of this research show:

- The divergent heat budget equation is a valid approach to the determination of horizontal advection.
- Q_n, the net surface heat exchange, exhibits an annual cycle and is therefore the term which creates the cyclic trend in $\partial H/\partial t$. The other DHB expressions fluctuate as pulses and serve to enhance or suppress the trend in surface heat flux.
- The large pulses in $\partial H/\partial t$ are the result of large pulses of horizontal thermal advection and, to a small degree, are influenced by the pulses of H_{div}.
- During the years 1968-1970, there were five significant horizontal advective anomalies, each distinguished by an initial cooling trend in conjunction with a sharp salinity decrease, followed by an advective warming period and salinity increase throughout the entire 250m column. These large advective cycles coincided with the largest of the changes in mean monthly salinity.
- The change in salinity is in response to translation of the Subtropic/Subarctic water mass boundary zone. Cold horizontal advection is a result of the intrusion of Subarctic water while advective warming is indicative of a return of the Subtropical water mass.

- Horizontal advection and H_{div} do not necessarily fluctuate in phase. A period of upwelling (H_{div} negative) serves to suppress the salinity change at 200m due to horizontal advection by mixing upward the higher salinities from the lower portion of the intruding Subarctic halocline. Conversely, downwelling (H_{div} positive) enhances the salinity decrease due to horizontal advection.

- The pulse-like nature of these five events is suggested to be in response to a non-dispersive baroclinic Rossby disturbance whose wave-like characteristics are responsible for the depression of the southern edge of the Subtropic/Subarctic transition zone into OWS N. Intrusions of Subarctic water occur approximately every 7 to 8 months. The duration of each intrusion is about 3 to 4.5 months.

- Other horizontal advective anomalies occurred in the period 1962-1967, but remain unsubstantiated by any changes in oceanic physical properties. In particular, a distinct lack of documented salinity data for this period prevented the examination of any thermohaline response to horizontal advection. However, these anomalies are, as in 1968-1970, non-seasonal in occurrence and exhibit the same characteristic period and duration.

APPENDIX A

HORIZONTAL ADVECTION EVENTS

The details of each horizontal advection event are presented in Figure 10. Each event is divided into a cooling trend (A) and a heating trend (B). Each of these trends is associated with a salinity change throughout the column, values for which are incremented at the surface, 50m, 150m, and 200m and are listed in Table II. Note that cool advection is always associated with a reduction in salinity and that salinity increases during periods of advective warming. The large change in salinity at 200m during Event 4 occurs because H_{div} is out of phase with horizontal advection.

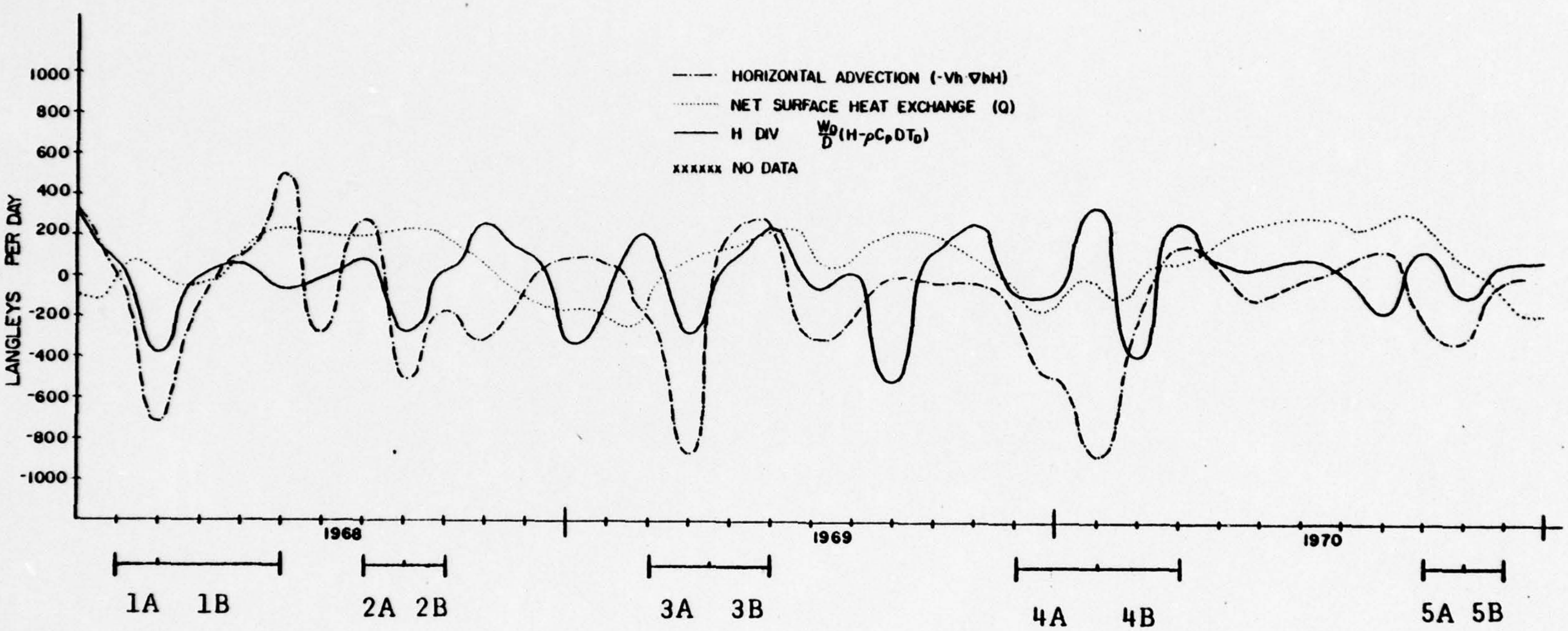

Figure 10: Major events in horizontal advection ($-\vec{V}_h \cdot \nabla_h H$) for 1968-1970.

Table II: Salinity changes (°/₀₀) during horizontal advection anomalies

Event		Salinity Surface	Change 50m	150m	200m
1A	$-\vec{V}_h \cdot \nabla_h H$ Cooling	-0.26	-0.19	-0.20	-0.18
2A		-0.14	-0.18	-0.11	-0.15
3A		-0.11	-0.13	-0.20	-0.10
4A		-0.14	-0.15	-0.10	-0.34
5A		-0.28	-0.17	-0.12	-0.06
1B	$-\vec{V}_h \cdot \nabla_h H$ heating	+0.25	+0.19	+0.14	+0.23
2B		0.24	0.13	0.05	0.01
3B		0.26	0.20	0.30	0.22
4B		0.30	0.27	0.11	0.08
5B		0.10	0.12	0.10	0.05

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